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IMPACT OF SOLAR WATER HEATING SYSTEMS ON AN ELECTRIC UTILITY

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ABSTRACT

Water heating is the second largest user of energy in the residential sector. Replacement of conventional water heaters by solar domestic hot water systems (SDHW) with electric backup has the potential to reduce both energy use and power demand. A method based on simulation for determining the impact on a utility of an alternative such as SDHW systems is described.

For both conventional and SDHW systems, a large number of simulations were performed that covered a wide range of system characteristics and load profiles. A random selection process was used to change each individual simulation by selecting characteristics within specified limits from a uniform distribution. Simulations were done for August in Madison, WI, and the results used to estimate the impact on energy use and demand on a hypothetical utility.

Smaller groups of the different simulations were selected to determine the number necessary to predict the impact. A single simulation of the average system with the average load is sufficient to predict the average energy use. However, a larger number, about 400 in this study, was necessary to estimate the demand.

Solar water heating systems with a 62% solar fraction reduced power demand over that for conventional water heating systems by 15% to 30% during a peak period of 1 to 4 PM. However, the SDHW demand is generally not coincident with utility systems' maximum peak demand, and this effectively eliminates demand during critical periods. Control strategies for SDHW systems can essentially eliminate the on-peak demand. SDHW systems may have a significant positive impact on a utility.

1. INTRODUCTION

Many utilities are approaching their maximum generating capacity during peak hours. As a consequence, they are faced with the decision either to build new capacity or to reduce peak demand. Since the construction of new generating capacity is expensive, utilities are considering methods to delay or avoid new construction. One technique to reduce peak demand is to install solar domestic hot water systems for residential customers. Most utilities in the U.S. are summer peaking utilities with peak system demands in the early afternoon in summer due to air conditioning. Since solar systems perform very well during this time, they have the potential to reduce peak demand (8,4).

Domestic water heating is the second largest user of energy in the residential sector (2). The total load and usage pattern varies for different consumer groups, and also from day to day for the same household. The diversity in use among different users and the day-to-day variation makes the evaluation of alternatives difficult. In this study, simulation techniques are employed to evaluate the impact in energy use and demand on a utility district due to replacement of conventional water heaters with solar systems.

2. METHODS

Both conventional and solar domestic hot water (SDHW) systems were simulated using TRNSYS (5). In the typical electric water heating system, hot water is removed from the top of the tank and cold water from the mains enters the bottom. The water is heated by an electrical heating element located in the bottom of the tank. This heating element is either on at full power or off. In the typical single tank solar domestic hot water system the heating element is located in the upper third of the tank and heats water when the solar supply is insufficient. Similar to the conventional system, the heater element is either on or off. The thermal characteristics of the two systems were chosen to represent current residential practice, and are given in Table 1.

Table 1. Characteristics of the conventional and SDHW systems

	Conv	SDHW	Range
Heater power (kW)	3	3	-
Set temperature (C)	55	55	-
Controller deadband (C)	6	6	± 50%
Tank volume (l)	240	800	± 40%
Tank UA (W/m^2-K)	2.6	2.6	± 50%
Surroundings temp (C)	20	20	-
Mains temperature (C)	7	7	-
Collector area (m^2)	-	7	± 30%
Collect. F_RU_L (W/m^2-K)	-	3.3	± 20%
Collector F_R (ta)	-	0.65	± 20%
Collector tilt angle	-	45	± 30%

The hot water load profile for the system was composed of a number of different hourly profiles to represent the diversity found in practice. In this study, 18 different profiles were employed. Some were adapted from data (1, 2, 6) while others were created as "reasonable". In general, the profiles showed a greater use during the daylight hours, with peaks in the morning and late afternoon. The average total daily load was 286 l (75 gal.).

3. RESULTS

3.1 Average System Performance

The average, or baseline, SDHW and conventional systems were simulated for the month on August in Madison, WI., for the 18 different load profiles. The performance in terms of energy use and power demand were compared. The simulation results for the first two days of August are shown in Figure 1. The dotted line represents the average hot water load for all of the systems. The dashed line represents the electric power required by the conventional water heater. The heater turns on and stays on until the tank temperature reaches the set point temperature and then turns off. The water temperature drops due to the load and losses to the environment until it is below the lower set point, at which time the heater turns on.

The electric power required by the backup electric heater of the SDHW system is shown as a solid line. There is similar behavior to the conventional system in that the heater cycles on and off. The difference is that the heater for the SDHW systems stays off for a much longer period of time since there is energy supplied to the tank by the solar collector.

Both systems supply the same hot water load of 1.78 GJ. The conventional electric systems consumes 1.86 GJ to meet the load and the losses, whereas the SDHW requires only 0.64 GJ to meet the same load and the losses. The solar fraction is 65%.

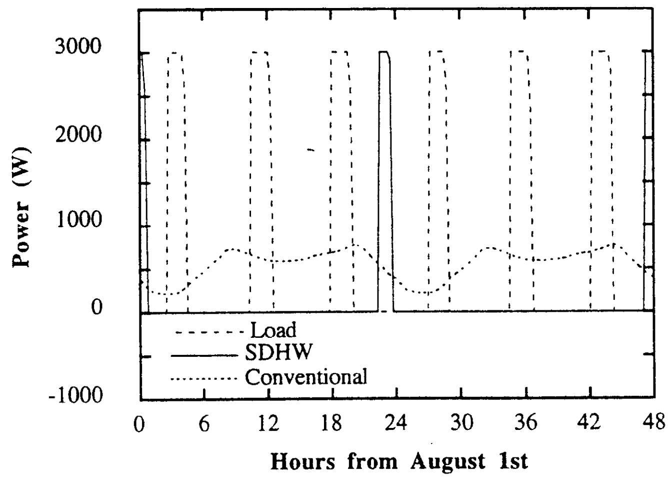

Fig. 1. Electric power demand for the first two days of August.

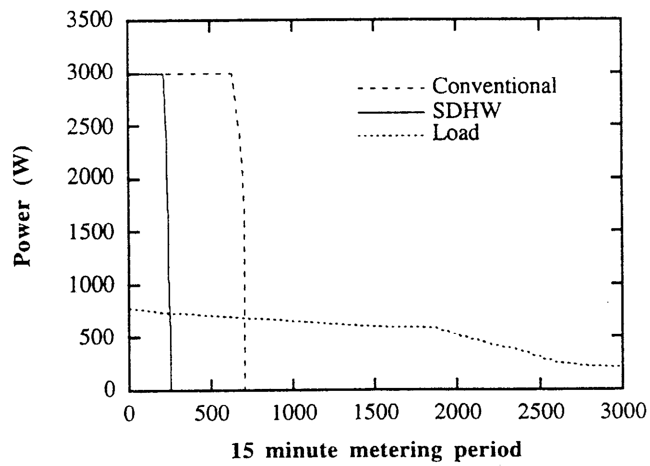

Fig. 2. Ordered frequency distribution of the demand in August.

An ordered frequency distribution for the power demand is shown in Figure 2. The distribution is obtained by ordering the power consumed in 15 minute periods from highest to lowest value. The figure shows that the peak electric power for the average SDHW system and the average conventional system are identical and equal to the maximum power of the electric heater. The conventional system has a broader band that reflects the greater energy use. For the simulated average systems, the electric power demand impact on the utility is the same for both conventional electric and SDHW systems.

A single SDHW system decreases the energy consumption, as expected. However, the peak power demand is the same for both conventional and SDHW systems; the heater is either on or off. However, for many systems, all heaters will not be on and off at exactly the same time. The systems are different,and loads are different in pattern and magnitude for different households. Therefore, the power demand from the simulation of an average system will be different from that from the simulation of many systems.

3.2 Results for Many Systems

In a utility district with many conventional and SDHW systems, each system will have a different impact. The system characteristics and hot water use pattern will be different for each installation. In order to simulate the different systems, random numbers chosen from a uniform distribution were used to modify the base case system parameters and water loads within specified limits. For each single simulation,each parameter was determined by a specific, randomly chosen value. The ranges for the parameters are given in Table 1. The heater power and the set temperature were not varied.

The hot water load profile varies from household to household and even within a specific household from day to day. To account for this fact, 18 different hot water load profiles were used in the simulations. A hot water load pattern was selected randomly for an individual simulation out of the pool of different load patterns and modified for each day of the simulation by randomly shifting it in time by plus and minus one hour and scaling by a random number between 0.75 and 1.25.

Simulations were then performed. Each conventional system was paired to a SDHW system with the same load to ensure that the same total load was experiencedby the utility for both systems. This models what would happen when a conventional tank is replaced by a SDHW system in the same household.

A total of 10,000 individual simulations were performed, and the results were combined into 100 groups of 100 simulations. Each group of 100 had a random selection of loads and systems characteristics. The resulting power demands and energy use were averaged. The average hot water load is 1.78 GJ. The average electrical energy required to meet this load is 1.85 GJ for the conventional electric system and 0.70 GJ for the SDHW system. The average solar fraction is 62%.

The instantaneous electrical power demand of 4,000 randomly selected systems normalized to one system is given in Figure 3 for the first two days in August. It can be seen that the electricity demand of the conventional system follows the hot water load plus some nearly constant losses. The power for the SDHW system is almost the same in the night and in the early morning hours. Since these first two days of August have high solar radiation, the solar system performs very well from about 6:30 AM on. Almost no electric backup is required. Obviously, the solar energy supplied is dependent on the weather and differs from day to day, whereas that of the conventional system is almost the same every day.

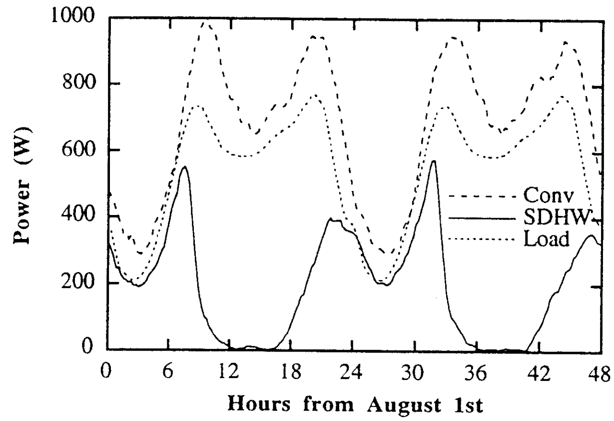

Fig. 3. Electric power demand for 4,000 conventional systems for the first two days of August.

The impact of the SDHW system can be described by computing the reductions in power and energy demand by the SDHW system. The ratio of the maximum electric power demand of the SDHW to the conventional electric system P* and ratio of electrical energy use Q* are defined as:

$$P^* = \frac{P_{max,\ SDHW}}{P_{max,\ conventional}} \tag{1}$$

$$Q^* = \frac{Q_{SDHW}}{Q_{conventional}} \tag{2}$$

Figure 4 shows the ordered frequency distribution of the power demand for the conventional and SDHW systems and the load for the month of August. The maximum power ratio is the ratio of the two left-most points for the conventional and SDHW systems. The value of P* is 0.79 and shows that the solar system reduces the peak demand by 21% over that of the conventional system. The energy ratio Q* is the ratio of areas under the demand curves and equals 0.38 (i.e., one minus the solar fraction).

It is assumed that the utility peak period is from 1:00 to 4:00 PM (other periods could have been chosen). The ordered frequency distribution of the power demand during this period is given in Figure 5. The maximum power ratio is 0.70 and the energy ratio is 0.09.

Figure 5 shows that the electrical demand for the SDHW system is greater than 150 W for only 13% of the 15 minute periods during this assumed peak period, and greater than 300 W for 9% of the time.

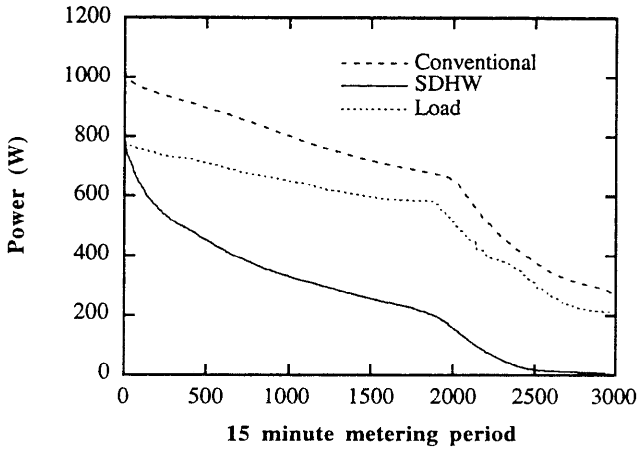

Fig. 4. Ordered frequency distribution of the demand in August.

Table 2 gives the number of days with a power demand above a given value for both the SDHW and the conventional electric system. There are three days during the month when the electric demand of the SDHW system is over 450 W and six days over 150 W during the hours from 1:00 to 4:00 PM, whereas the demand of the conventional electric system exceeds 750 W in all but one day during August.

Table 2. Number of days with a power demand above a specified value for one or more 15 minute period

	Number of Days					
limit (W)	150	300	450	600	750	900
All: Conv	31	31	31	31	31	30
SDHW	31	31	30	19	5	0
Peak: Conv	31	31	31	31	30	0
SDHW	6	3	3	0	0	0

The monthly average daily irradiation for Madison in August is 19.4 MJ/m^2. For the three days in which the power demand of the SDHW systems was over 300 W during the peak period, the daily solar irradiation was found to be 7.5 MJ/m^2, 6.3 MJ/m^2, and 3.1 MJ/m^2, respectively. The daily irradiation values were 11.5 MJ/m^2, 13.7 MJ/m^2, and 10.0 MJ/m^2 for the three days in which the maximum power demand of the SDHW systems was between 150 W and 300 W. As expected, the solar irradiation during the SDHW peak power demand days are considerably lower than the average.

The highest peak demand for the utility is caused by high air-conditioning loads during hot days, while the solar system peak demands occur during days with low solar irradiation. Presumably, these are "cool" days from the standpoint of air conditioning. Therefore, the peaks for the total utility load and for the SDHW systems may not be coincident. Thus the benefits of the SDHW system in demand reduction maybe greater than implied by the maximum demand fractions P*. During peak periods, the power demand for water heating is reduced from more than 750 W to less than 150 W. The value of P* provides a ``worst case" scenario.

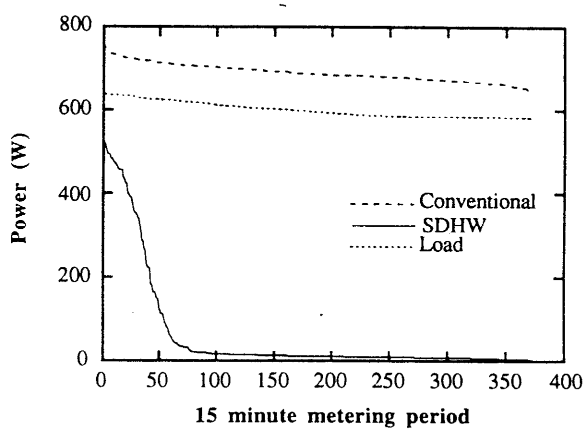

Fig. 5. Ordered frequency distribution of the power demand for August between 1:00 and 4:00 PM

The previous simulations were performed with 18 different loads selected randomly. The RAND profile (3, Figure 9.1.2) has been used as a "standard" hot water load to represent the average of many systems. Simulations were performed to investigate the impact of this different hot water load profile on the maximum demand and the energy use. The RAND hot water load profile was randomized for each day of the simulation by shifting it in time up to 1 hour backward or forward and by scaling it by a factor between 0.75 and 1.25. The results are qualitatively similar to the results for the other profiles, Figure 4.

Table 3 gives the maximum power demand and energy fractions for the two different sets of load profiles. The energy fractions are the same. The maximum power demand fraction for the hours from 1:00 to 4:00 PM are different although the maximum power demand fractions for all hours are essentially the same.

Table 3. Maximum power demand and energy fractions for two sets of load profiles

	All profiles		RAND profiles	
	P*	Q*	P*	Q*
All hours	0.78	0.38	0.79	0.35
Peak.	0.66	0.06	0.86	0.08

For both profile sets, the peak electrical demand of the SDHW systems occurs for only three days in August which have low solar irradiation. The electrical demand of the conventional electric systems is the same every day. Within reason, the choice of a profile shape does not appear to affect the on-peak impact.

3.3 Number of Simulations Required to Estimate Impacts

The estimates of demand and energy reductions were based on simulations of 4000 systems. In application, it would be desirable not to need to simulate all proposed systems in order to estimate impacts. The use of less than the full set of simulations was explored.

A total of 10,000 simulations were performed and grouped in sets of 100 runs each to yield 100 sets of 100 systems. Maximum electric power demand fractions and energy fractions for sets of run sizes of 400, 1,000, 2,000, 4,000 and 10,000 were obtained by randomly selected groups of size 100. A "bootstrapping" technique was used in which each selected set was put back into the pool and could be selected again, mimicing the situation in which there might be more than 10,000 systems.

In Figures 6 and 7, the maximum electric demand and energy fractions for different group sizes for all hours and the demand period are shown for different run sizes. There are 100 sets for the group size 100 and 20 sets for the other run sizes. The solid lines represent the results for all 10,000 runs.

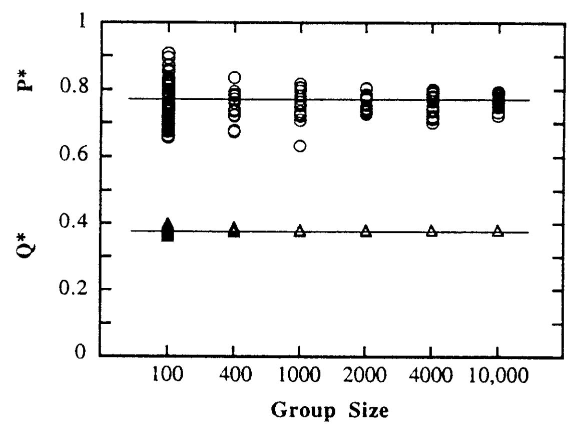

Fig 6. Maximum power and energy ratios in all hours for different group sizes.

The variation in the energy fraction is relatively small. Even with the large variations in system characteristics and loads, a set of 400 runs gives a good estimate of the total energy use; the standard deviation is less than 1%. In fact, the simulation of one average system would give good a good estimate since non-linear interactions between such factors as collector area and total load size are small.

The spread of the maximum power demand fractions is considerably larger. The increase in group size from 100 simulations per set to 400 decreases the spread of the results; the standard deviation of run size 400 is 4%. Further increases in numbers of simulations included do not necessarily produce a better estimate of the average. A few hundred simulations areneeded to estimate the maximum power demand fraction within 4%.

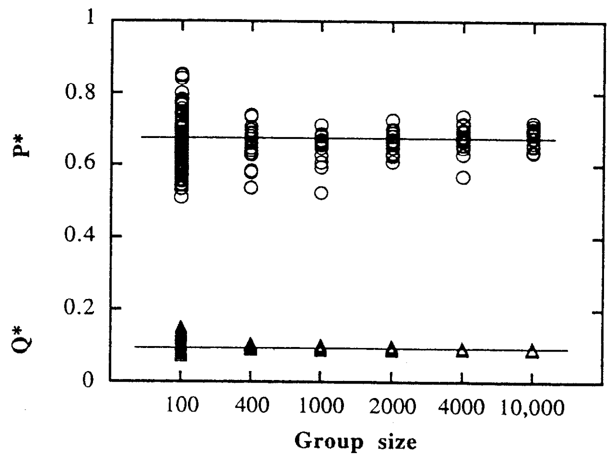

Fig . 7. Maximum power and energy ratios for the demand period for different group sizes.

3.4 Control Strategies to Reduce the Peak Demand

The ordered frequency distributions for the peak demand period, Figure 5, together with the results in Table 2 show that the on-peak load factor for the SDHW systems is very low, and poor from a utility point of view. There are only a few times during the month when the backup heater for the solar system is required. This implies that the SDHW systems could be controlled to eliminate on-peak use completely. As an example of control impact, two sets of simulations were performed in which the set point temperature was changed with time. For the first simulations, the set point temperature was increased to 65 C at noon and decreased to 45 C at 1:00 p.m and reset to 55 C the rest of the time. For the second simulations, the set point temperature for one half of the systems is increased at 11:00 AM and at noon for the other half. These strategies allow the tank to be heated before the utility peak time and then use stored energy only during the peak period.

Both strategies eliminated electrical use completely during the demand period. However, peaks were produced during the non-demand period when the thermostats were turned up. The average demand of the SDHW systems became 3000 W since all of the SDHW heaters turned on and was nearly four times that of the uncontrolled level (Figure 4).

When this control strategy was also applied to the conventional systems, the demand was also 3000 W. The SDHW systems offered no reduction in demand over the conventional water systems. An improved strategy might be to spread the increase of the set point temperature over a larger time period such as three or four hours.

4. CONCLUSIONS

The simulation of one individual (average) conventional or SDHW system yields an accurate measure of the energy consumption. However, the peak electricity demand is the same for both conventional and SDHW systems and equal to the heater capacity. The simulation of the instantaneous performance of a single system cannot be extrapolated to a large number of installations.

Multiple simulations that model the diversity found in a utility district show significantly lower peak power demands. The average power demand for the ensemble is lower by a factor of three for the conventional system and by a factor of four for the SDHW system than for the single average system.

The SDHW system significantly reduces the peak electrical demand over that of the conventional electric. For a utility with a peak load period between 1:00 and 4:00 PM, the peak demand for the SDHW system is about two-thirds that of the conventional electric system. The energy fraction is independent of the shape of the hot water load pattern, but the maximum power demand fraction is dependent on the hot water load pattern. Further study is needed in this area.

Control strategies can eliminate the energy use for both the SDHW and the conventional electric system during the demand period. However, the strategy explored in this study produces a system peak demand right before and after the on-peak period. Other control strategies that distribute the control action in time may be beneficial.

For the SDHW systems considered here, there is a demand during the peak period only three days in the month. These three days have low incident irradiation, and are "cool" in terms of air conditioning. The utility peak and the peak of the SDHW system probably are not coincident, and the demand during utility peak load is reduced more than indicated. The maximum power demand fraction is a worst case measure of the demand reduction by the SDHW system.

The results for many (10,000) systems may be estimated by a smaller number of simulations. For a set size of 400 randomly selected simulations, the energy reductions are estimated within 1%. For the maximum demand fractions 400 simulations yield results which are within 4% of the average for all hours and 6% for the peak period.
Different system simulations yield different energy and power reductions. However, all show that SDHW systems consume significantly less energy and reduce the peak power demand over conventional electric water heating systems.

5. ACKNOWLEDGMENTS:

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